# RANGE ESTIMATION TECHNIQUES IN SINGLE-STATION THUNDERSTORM WARNING SENSORS BASED UPON GATED, WIDEBAND, MAGNETIC DIRECTION FINDER TECHNOLOGY

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## ABSTRACT

Gated, wideband, magnetic direction finders (DFs) were originally designed to measure the bearing of cloud-to-ground lightning relative to the sensor. A recent addition to this device uses proprietary waveform discrimination logic to select return stroke signatures and certain range dependent features in the waveform to provide an estimate of range of flashes within 50 kilometers. In this paper, we will discuss the enhanced ranging techniques designed and developed by Lightning Location and Protection, Inc, for use in its single-station thunderstorm warning sensor. Included in the paper will be the results of on-going evaluations being conducted under a variety of meteorological and geographic conditions.

## INTRODUCTION

The LLP thunderstorm sensor (TSS) is a single-station thunderstorm warning system that provides real-time information about the occurrence of cloud-to-ground lightning in and around an area of concern. This information is used in a variety of ways to improve safety and effect cost savings. Typically, the TSS warnings are used to clear personnel from exposed areas, to shut down hazardous operations, and to switch sensitive equipment over to backup power. The TSS indicates the approach and the direction of approach of a thunderstorm to the area of concern as well as warning of the occurrence of cloud-to-ground lightning within the area of concern. When the storm has passed and no cloud-to-ground lightning has been detected within the area of concern for a certain time period (usually 15 minutes), the warning is lifted, indicating it is safe to resume normal operations. Some typical applications are entertainment parks, airport operations, construction projects, and sensitive manufacturing plants.

The TSS is a major improvement over any thunderstorm warning device previously available because it incorporates the same patented technology that is used in the LLP lightning locating networks [1-4]. The sensor detects the presence of thunderstorms by detecting cloud-to-ground lightning on a flash-by-flash basis. For each stroke in the flash the sensor determines the time, the direction, the signal strength, the polarity, and the change in the electrostatic field associated with the stroke. The detected waveforms must pass some fairly restrictive waveform criteria tests to be considered valid return strokes. These tests eliminate background interference and cloud lightning (cloud-to-cloud, intra-cloud etc.).

The location of the thunderstorms is inferred from flash data that have the following performance properties:

- The flash identification is very good. For a properly sited sensor the false rate due to background noise is essentially zero. The only false flashes are due to cloud lightning that is misidentified as cloud-to-ground. Fewer than 1% of the waveforms accepted by the sensor are due to non-cloud-to-ground lightning. These do not cause a problem because they only occur during a thunderstorm, and they are such a small fraction of the events that they do not appreciably influence the thunderstorm algorithm.

- The flash direction is very accurate (+/- 1 degree).

- The flash time measured relative to the TSS clock is precise (+/- 1 millisecond).

- The sensor is a long-range instrument. Storms can be sensed as far away as 100 nm.

Given the difficulty of determining range with a single-station sensor, one might recommend using location information from a lightning locating system to calculate the range. This would certainly be a viable alternative, but a single-station sensor offers a number of important advantages:

Cost
: A locating system requires at least two sensors and a central analyzer to calculate the location. In addition, remote sites must be located and communication between the sensors and the central analyzer set up.

Installation
: Since a single-station sensor is located at the facility of concern , siting and communication issues can usually be performed by local personnel.

Accuracy
: Since a single-station sensor is located at the area of concern, its systematic errors are relative to the area of concern, and are guaranteed to have a relatively minor effect.

Control
: Since the entire warning system is under direct control of those most concerned with its proper operation, maintenance and operational priorities can be tailored to meet the needs of the facility.

Performance
: Since the warning system is tuned for optimal performance in the immediate vicinity of the sensor, a single-station sensor is frequently able to offer higher short-range detection efficiency and directional accuracy than a wide-area locating network.

Studies of the spatial distributions of cloud-to-ground strike points has shown, that for small cells the mean distance between successive flashes is from 3.2 to 4.2 km (Krider [5]). This means that, if any lightning is detected within this distance, it is time to issue a thunderstorm warning.

Since the function of the TSS is to detect the presence of thunderstorms, as opposed to locating individual flashes, the sensor classifies each flash as one of 4 ranges: 0-3, 3-10, 10-30, and beyond 30 nautical miles. The number of flashes in each classification during the last 15 minutes are used to determine the presence and position of thunderstorms. The range classification is not precise in that a flash near the edge of one classification has a finite probability of being assigned to the adjacent classification. The effectiveness of the range classification is completely characterized by the probability, as a function of range, of a flash being assigned to each of the four range classifications.

In this paper, we present the results of an experiment that was made to determine these four probability distributions. We also present the results of a number of experiments that test how well the TSS agrees with human observers and with radar.

The sensor has 3 receiver channels, each with a bandwidth of 1 kHz to 350 kHz, that detect the north-south and east-west components of the horizontal magnetic field and the vertical component of the electric field. Figure 1 shows typical waveforms for cloud-to-ground return strokes at 2, 5, 10, and 50 kilometers. The initial sharp rise to a peak is the radiation field due to rapid turn-on of the return stroke current when a leader has approached close enough to ground to initiate a discharge. This radiation field returns to zero over a period of 50 $\mu$sec as the current slowly turns off as charge in the cloud is neutralized. This can be seen in the 50 kilometer waveforms of Fig. 1 which are essentially pure radiation fields. Note that the magnetic and electric waveforms at 50 kilometers are quite similar to each other as they should be for the radiation fields. The electric and magnetic waveforms for 2, 5, and 10 kilometers differ from each other considerably after the initial radiation peak. The electric field waveform has a ramp due to the change in the vertical component of the electrostatic field. This is primarily a dipole effect due to transporting charge between the cloud and ground, and it should be inversely proportional to the range cubed. Likewise, the magnetic waveforms have a hump due to induction fields, and are inversely proportional to the range squared. In each case the waveform for the first stroke (solid line) is significantly larger than that of the second stroke (dashed line). The theoretical basis for these assertions is contained in Uman [6].
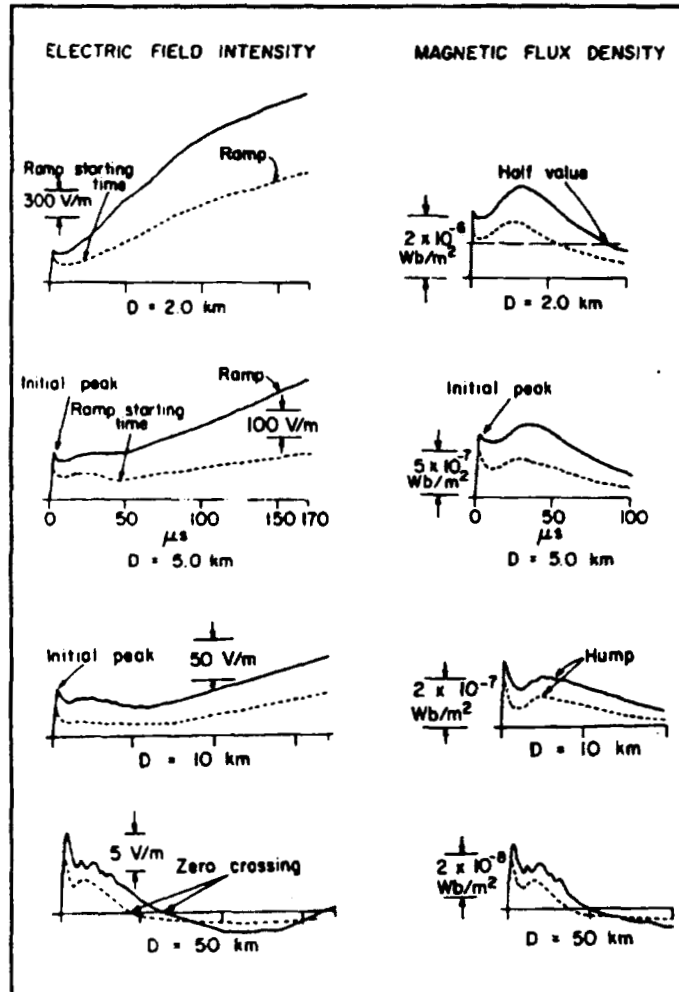


Figure 1 Typical electric and magnetic waveforms for cloud-to-ground return strokes at ranges of 2, 5, 10, and 50 km (adapted from Lin et al. [7]). The solid lines are the first stroke, the dashed curves are subsequent strokes.

The sensor samples all 3 channels simultaneously at the radiation field peak and then resamples the electric field channel at 170 $\mu$sec after the peak. The electric field is sampled at 170 $\mu$sec to be consistent with Lin et al. [7]. This time is fairly arbitrary. It could be any time that gives a measure of the ramp. The magnetic field components are used to calculate the direction to the stroke and the magnitude of the radiated field peak (the signal strength). The magnetic field components are used to calculate the signal strength because the gain of the magnetic field antennas is nearly independent of siting, whereas the electric field antenna gain depends strongly on siting. The signal strength is approximately proportional to the peak current in the return stroke and inversely proportional the range as shown in Eq. 1.

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$$SIGNAL = CONSTANT \times \frac{CURRENT}{RANGE} \qquad (1)$$

The inverse range dependence arises due to conservation of energy, as the radiated energy is spread out over a spherical shell with a radius equal to the range. The "constant" is empirically determined for the sensor from the signal strengths of flashes at known ranges. In order to do this, it is assumed that the median of the range-normalized signal strength distribution corresponds to the median of measured current distributions.

If the return stroke current were known for each flash, then Eq. 1 could be used to calculate the flash range. Since the current is not known for a single-station sensor, the range can be estimated by assuming that the current is equal to the median current. Due to the large variation in the return stroke currents, this is not a very good estimate of the range. However, it is useful for distinguishing close lightning from distant lightning, where the range variation is large enough that it dominates the uncertainty in the current.

The primary quantity used by the LLP sensor to determine the range is the ratio of the electric field sampled at 170 $\mu$sec to radiation peak in the electric field, which is referred to as the relative electric field change (REFC):

$$REFC = \frac{ELECRIC\ FIELD\ AT\ 170\ \mu SEC}{ELECTRIC\ FIELD\ RADIATION\ PEAK} \qquad (2)$$

The value of the REFC depends mainly on the range. This is because both quantities in the ratio are roughly proportional to the total charge transferred by the return stroke, which allows the charge dependence to cancel out. The electric field at 170 $\mu$sec is a measure of the electrostatic field change, which, in a simple dipole model, is proportional to the total charge transferred times the height of the charge center. The value of the electric field radiation peak is proportional to the peak current, and given that all return stroke waveforms have approximately the same shape, and that the total charge is the integral of the current, the total charge is approximately proportional to the peak current. The dependence on total charge for both quantities is somewhat rough because of the large variations in the spatial distributions of the charges involved.

Fig. 2 shows the combined data of Lin et al. [7] and Tiller et al.[8]. These data show a large scatter of the value of the REFC at a particular range, but there is a clear correlation with range. Fig. 2 also shows that the REFC for first strokes tends to be larger than that for subsequent strokes. Presumably this is an effect of the side channels of the first stroke.

The range-dependence of the REFC is approximately the reciprocal of the range squared. This is because the radiated field is inversely proportional to the range, and a dipole field, which dominates the field at 170 $\mu$sec, is inversely proportional to the range cubed. This strong range-dependence means the REFC is useful only for ranges of 20 km or less.

An important fact to note is that since both quantities in the REFC ratio are measured on the electric field channel, the antenna gain cancels out, resulting in REFC being insensitive to sensor siting.

As mentioned above, the TSS assigns each flash to one of four ranges: 0-3, 3-10, 10-30, and beyond 30 nm. For flashes within 3 and 10 nm, range is determined on the basis of the REFC and signal strength of the first stroke. The remaining flashes are assigned to 10-30 or beyond 30 on the basis of signal strength alone. If the signal strength of a given flash exceeds the dynamic

range of the instrument (over-range), it will be automatically considered to be within 3 nm. The thresholds for the REFC at 3 nm criteria have been selected so that any flash with an REFC greater than the threshold has a probability of 0.9 of being within 3 nm.

The TSS maintains a running total of the number of flashes in each range region for a given interval, which is typically the last 15 minutes. The 3-10, 10-30, and beyond-30 regions are divided into octants. A red warning is issued whenever one or more flashes have occurred in the 0-3 region, or whenever 6 or more of the 3-10 octants have 1 or more flashes.
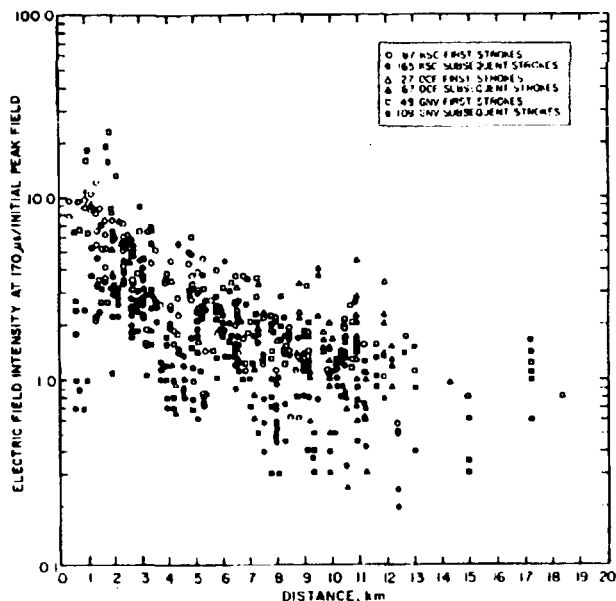


**Figure 2** REFC for close first and subsequent return strokes (combined data from Tiller et al. [8] and Lin et al. [7]).

## EVALUATION OF THE RANGE ALGORITHM

Over the course of the last several years, LLP has invested considerable effort in the characterization, design, and execution of formal tests to evaluate the effectiveness of single-station thunderstorm sensors. Initially, LLP experimented with location techniques that were based exclusively on averaging the measured signal strengths of groups of flashes. In this early testing, human observers and radar records were the primary points of comparison. Although this ranging technique showed some promise, it was determined that the overall performance had to be improved if single-station technology was to provide an effective warning system.

With the addition of the REFC enhancement to the ranging algorithm in 1986, a substantial improvement was made in single-station ranging. However, it was realized that in order to properly measure this improvement, a standardized method must be established to characterize the operation of a single-station warning device. The first step in this process was a careful analysis of the factors affecting both the reporting instrument and the measuring instrumentation, as described in Neumann, et al. (1988) [9]. From this work, an initial test was undertaken during the summer and fall of 1988 in Tucson, using local facilities including a locating network and National Weather Service (NWS) observer reports. This initial work, which included ranging information based on REFC techniques, was reported in Neumann, et al. (1989) [10]. In addition to the observations related directly to the performance of the sensor, this experiment also provided an important opportunity to analyze the methodology and design of the test itself, and served as an important milestone for subsequent work.

In conjunction with the experiment to formally characterize REFC, described later in this paper, a carefully formulated test of the performance of the Thunderstorm Sensor (TSS) was undertaken in Tucson. In this test, the two TSS instruments were co-located inside a region of highly accurate performance of the LLP Tucson Research Network. In addition, data were collected from on-site human observers, NWS records from a manned weather station in the area, and NWS weather radar. The purpose of this test was not to characterize the sensor's

performance on individual flashes, but rather on properly monitoring the development, movement, and dissipation of thunderstorms in the vicinity.

The results of this experiment clearly indicated the benefit of an automated thunderstorm warning system. Not only did the sensor agree with the human observers in this test, the TSS was able to provide the warning earlier, since its measurements were not limited by line-of-sight or other local distractions. In addition, the TSS also provided a significant enhancement to the interpretation of NWS radar images by differentiating areas of highly convective activity from that of rain shafts from precipitation. The TSS also showed good agreement with the LLP locating network. Although, as one might expect, precise locations could not be obtained from the TSS, the approximate distance and direction reported by the TSS were consistently in agreement with the locations provided by the network. Moreover, the lack of erroneous reports from the TSS also indicates the important benefit of waveform discrimination for identifying lightning events. Incorrectly reporting the presence of lightning has been a chronic problem of many single-station warning devices, and no such events were identified in this field experiment.

In addition to this carefully instrumented and monitored test, there have also been other field experiments and operational commercial installations that have reported similar findings. In two instances, Thunderstorm Sensors have been placed near NWS field offices on the east and southeast United States coastlines for data collection. When NWS observers have had access to the data reported by the TSS, they have reported being able to detect thunderstorms at an earlier point in their development, and to better differentiate thunderstorm activity from heavy precipitation. In addition, commercial installations of the TSS at heavily used airfields in the upper mid-west, mid-south, and desert southwest have also returned anecdotal information of earlier and more accurate warning of thunderstorm activity based on using the TSS independently or in conjunction with other weather sources, such as radar, which has directly improved their operational efficiency.

To further quantify performance, in the summer of 1990 LLP performed a explicit test of the ranging algorithm. In this test, the Tucson LLP research lightning locating network was used to determine the flash range. The LLP network consists of 3 low-gain DF's with baseline distances of 36.1, 37.5, and 51.7 km, as shown in Fig. 3 (along with some sample flash data). The test took advantage of the fact that, since the DF's have comparable hardware to the TSS, the DF's can also measure the quantities necessary to calculate the REFC. During the test the DF's ran a special version of firmware that transmitted the electric field radiation peak and the electric field at 170 $\mu$sec along with the data normally send the central site. This data was recorded along with the flash location. The data was reprocessed off-line to calculate the REFC as a function of range. The network was run in this mode during the summer of 1990. The data presented below are all the negative flashes from 4 days at the peak of the monsoon (August 3, 11, 12, and 16) where a "good" location was calculated. A "good" location required that the range from one DF was less than 40 nm, that the time reported by the DF's be within 5 milliseconds, that the semi-major axis of one standard deviation error ellipse be



Figure 3  LLP Research Network, 1990

less than 0.5 nm, and, if all 3 DF's reported so that an optimized location could be calculated, that the $\chi^2$ per degree of freedom be less than 5. A standard error of 1 degree was used in calculating the $\chi^2$.
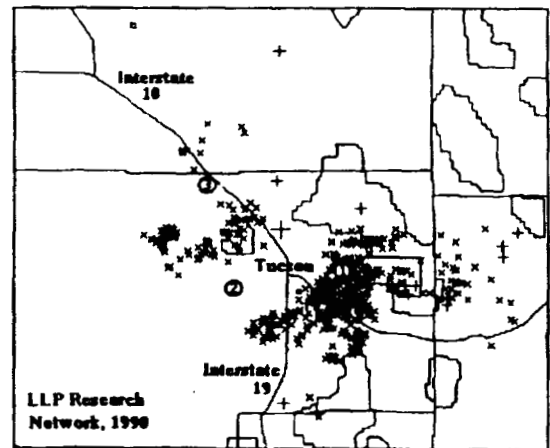
A total of 10,591 flashes were detected by the network in the 4-day sample. Most of these were too distant from the DF's to meet the requirements of a "good" flash. The final data sample consisted of 895 flashes with 2339 DF reports with a range less than 40 nm. The range distribution of the final data sample is shown in Fig. 4. If the flashes were distributed uniformly over the area of the network, this distribution would increase linearly with range starting at zero. The first three bins have been depopulated due to over-ranges, and due to being rejected by a waveform criterion that requires that any subsequent peak in magnetic field be smaller than the initial radiation peak. This criterion, which helps reject cloud discharges, is normally enabled in a DF, but it is disabled in a TSS because the induction hump in the magnetic waveforms (see Fig. 1) is larger than the radiation peak for return strokes close to the sensor. Ideally, this criterion should have been disabled for this test since the DF's were being used to simulate TSS's, but this could not be done due to other operational requirements of the network. The fall-off at distances greater than 20 nm is primarily due to the strict accuracy requirement and the short baseline of the network.

A scatter plot of the signal strength vs. range for this same sample of DF reports is shown in Fig. 5. The large scatter is due to wide log-normal distribution of return stroke currents. The signal strength is the only criterion used to classify flashes as beyond 30 nm or within 30 nm. This results in a rather slow fall-off of the probability at 30 nm for the 10-30 and beyond 30 classifications.

A scatter plot of the REFC vs. range for the data set is shown in Fig. 6. The scatter of the data in this plot is significantly less than in the signal strength scatter plot (Fig. 5). With the exception of eight or so (< 0.5%) outliers, the data falls in a fairly tight band with clear range dependence. This range dependence is consistent with the expected reciprocal range squared dependence as discussed above. Much of the data within 5 nm was not available due to the use of the second peak waveform criterion. If the data within 5 nm had been available, it is believed that much larger values of REFC would have been plotted, and the range dependence would be even more dramatic.
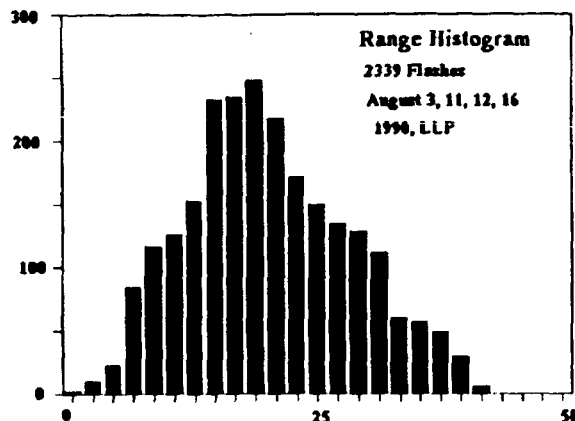


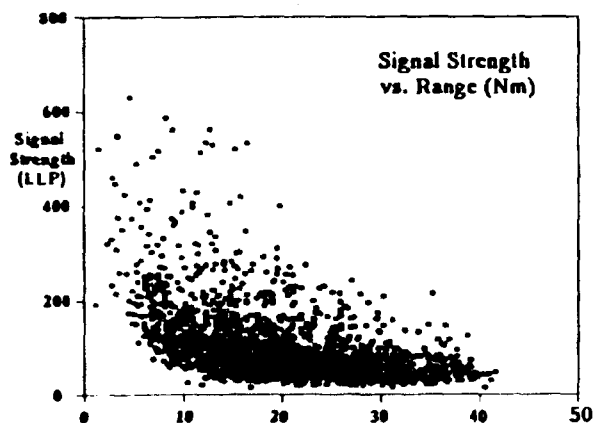Figure 4 Combined range distribution for all DF's.



Figure 5 Scatter plot of signal strength vs. range for all DF reports.
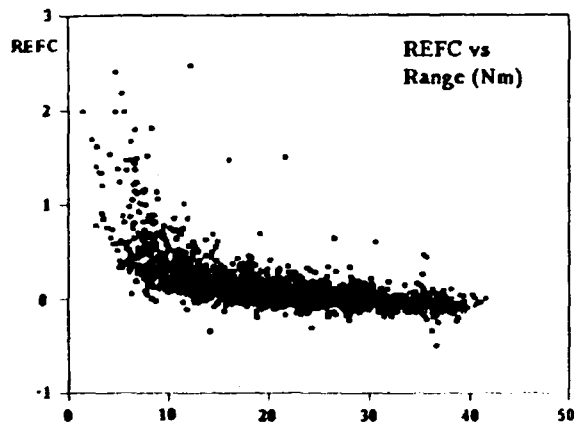


Figure 6 Scatter plot of REFC vs. range for all DF reports.

For this analysis, any flash with a first stroke signal strength less than 41.25 LLP signal strength units was classified as beyond 30 nm. The probability of a flash being classified as beyond 30 nm as a function of range is shown in Fig. 7. Each bin is the percentage of DF reports of the corresponding bin in Fig. 4 that had a signal strength less than 41.25 LLP units. This distribution would rise to 100% for large ranges if the data set included data beyond 40 nm. The value 41.25 was picked so that this distribution would have a value of approximately 50% at 30 nm. Note that the distribution does not go to zero until a range of 10 nm. This is due to return strokes with small peak currents.
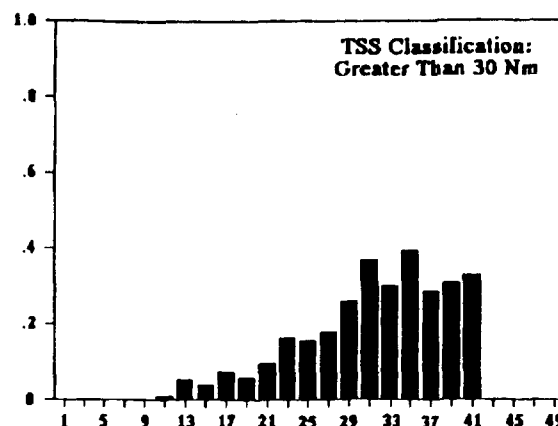
A return stroke was classified as 10-30 nm: 1) if the signal is between 41.25 and 75, or 2) the signal is greater than 41.25 and the REFC is less than 0.5. The probability of a flash being classified as 10-30 as a function of range is shown in Fig. 8. The cutoff at 10 nm is fairly sharp due the combined effect of the REFC and the signal strength criteria. The cutoff at 30 nm is very slow since it is due to the signal strength criteria alone. The effect of the signal strength criteria at 10 nm is much sharper than the effect at 30 nm because the slope of the inverse range dependence of the signal strength is 9 times greater at 10 nm than at 3 nm.
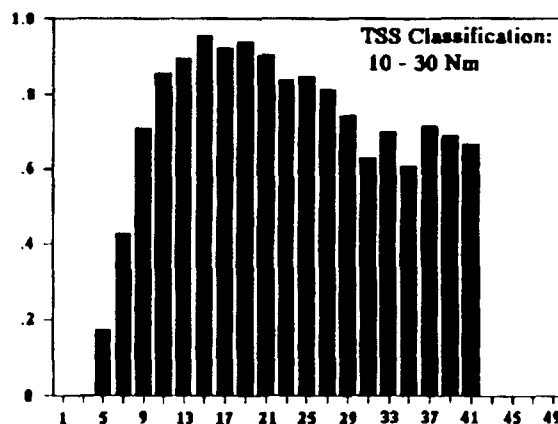
The criteria for 10-30 were picked so that the distribution is just starting to fall as the range is decreased from 10 nm. This tends to pull flashes from the 3-10 classification, but also prevents return strokes from outside 10 nm from being classified as within 10 nm. This is to prevent false alarms due to return strokes with large peak currents that are outside 10 nm.

A return stroke was classified as 3-10 nm: 1) if the signal strength is between 75 and 125 and the REFC is greater than 0.5 , or 2) if the signal is greater than 125 and the REFC is between 0.5 and 1.5. The probability of a flash being classified as 3-10 nm as a function of range is shown in Fig. 9.
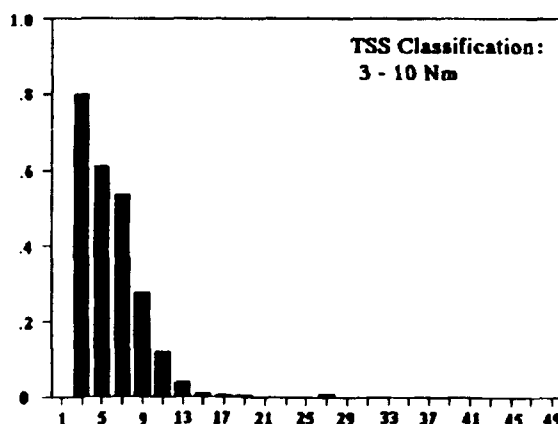


Figure 7 Probability of a flash being classified as beyond 30 nm.



Figure 8 Probability of a flash being classified as between 10 and 30 nm.



Figure 9 Probability of a flash being classified as between 3 and 10 nm.

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A return stroke was classified as 0-3 nm if the signal is greater than 125 and the REFC is greater than 1.5. The probability of a flash being classified as 0-3 nm as a function of range is shown in Fig. 10.

For this analysis, the same REFC thresholds were used for positive flashes as for negatives, but the signal strength thresholds were increased by a factor of 2 because median peak current for positive flashes is approximately twice as large as that for negatives. However, the positive flashes were not analyzed because of the very small data set from the monsoon thunderstorms used in this test.
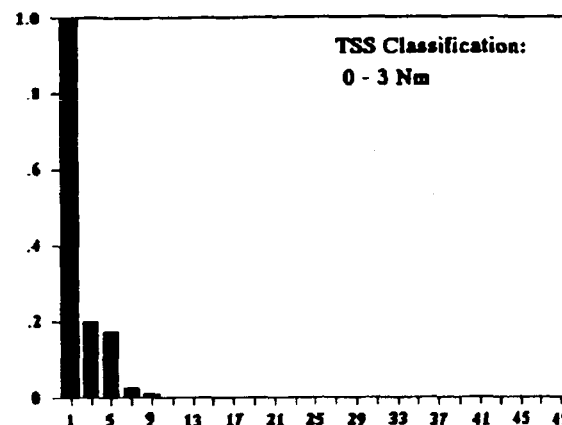


Figure 10 Probability of flash being classified as between 0 and 3 nm.

## CONCLUSIONS

The LLP Thunderstorm Sensor provides better thunderstorm warning than any previous single-station device, with performance comparable to, if not better than, that of a multi-station lightning locating system. A number of tests have shown good correspondence with human observers and radar, and an explicit test of the ranging algorithm has demonstrated excellent performance within 10 nm. The combination of signal strength and REFC (relative electric field change – see Eq. 1) provides sufficient range information to determine storm location and issue timely thunderstorm warnings. The instrument has been shown to have good correspondence with theory and previous experiments (see Figs. 5 and 6).

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